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Jet Propulsion Laboratory
California Institute of Technology

Thermal Operability Improvements for the Mars 2020 Rover Surface Mission

ICES Paper 2018-13

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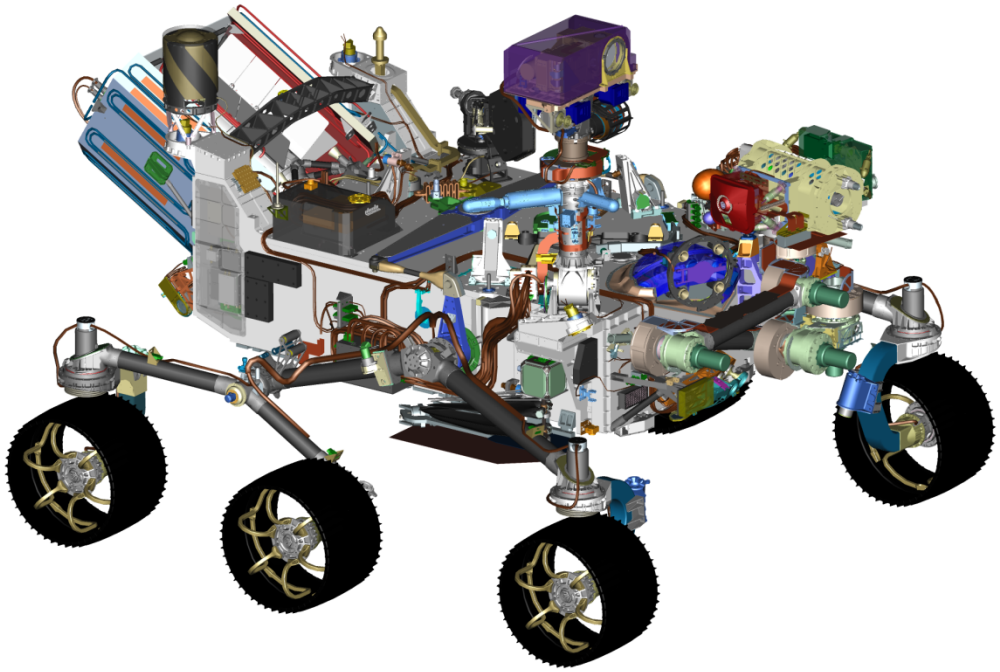
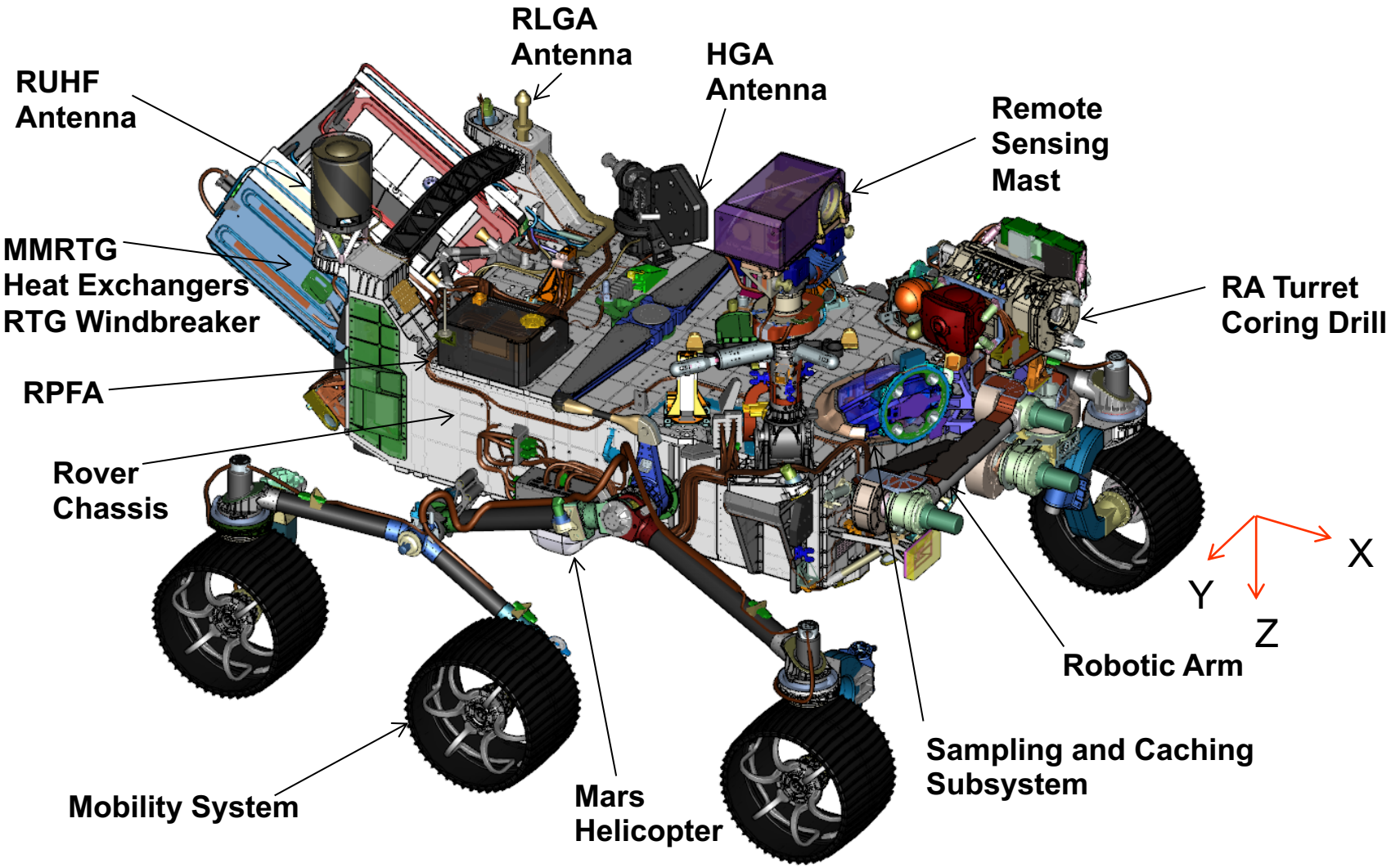


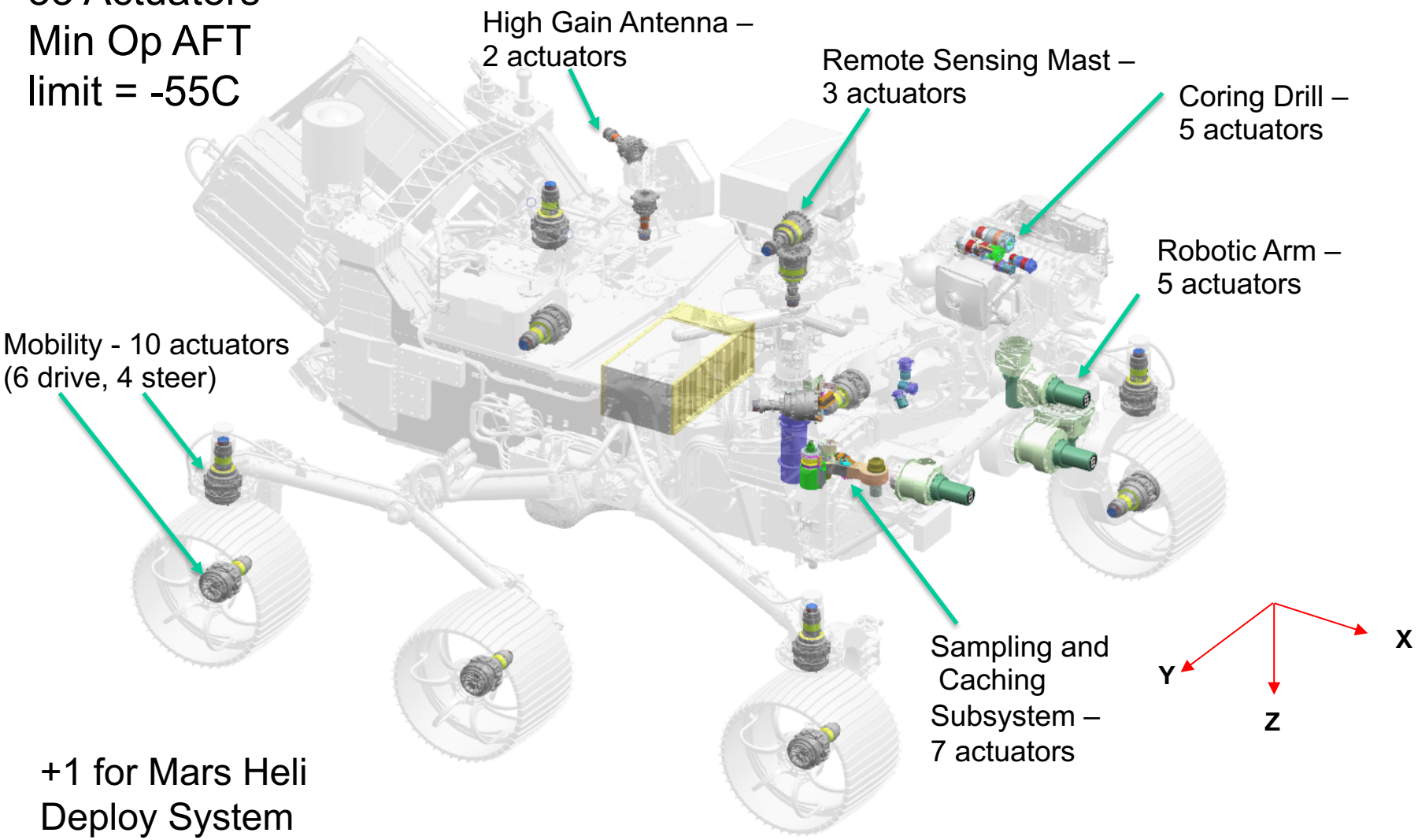
July 9-12, 2018

Mars 2020 Rover Deployed on Surface



Rover Motion Control System (MCS)

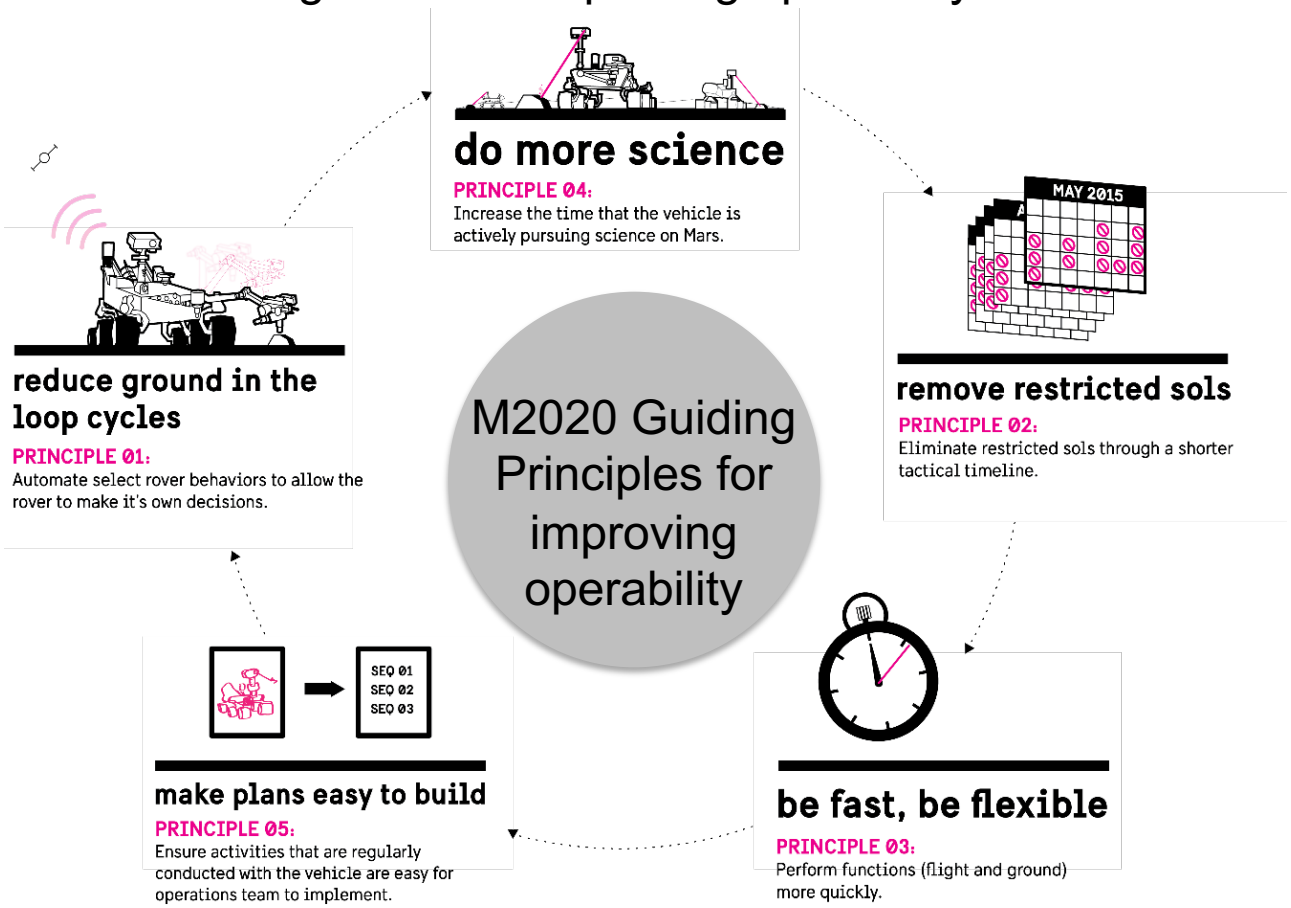
33 Actuators
Min Op AFT
limit = -55C



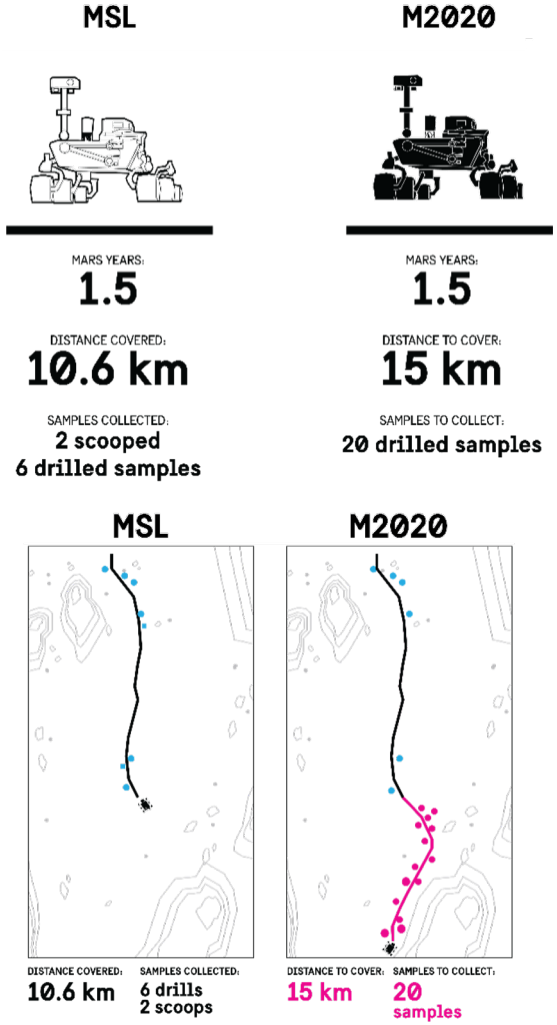
+1 for Mars Heli Deploy System

Operability Overview

- Significant mission performance gap between what MSL delivered and what M2020 Requires
  - Strong focus on improving operability of M2020



Comparison of MSL and M2020 Performance



*** Images from Jennifer Trosper**

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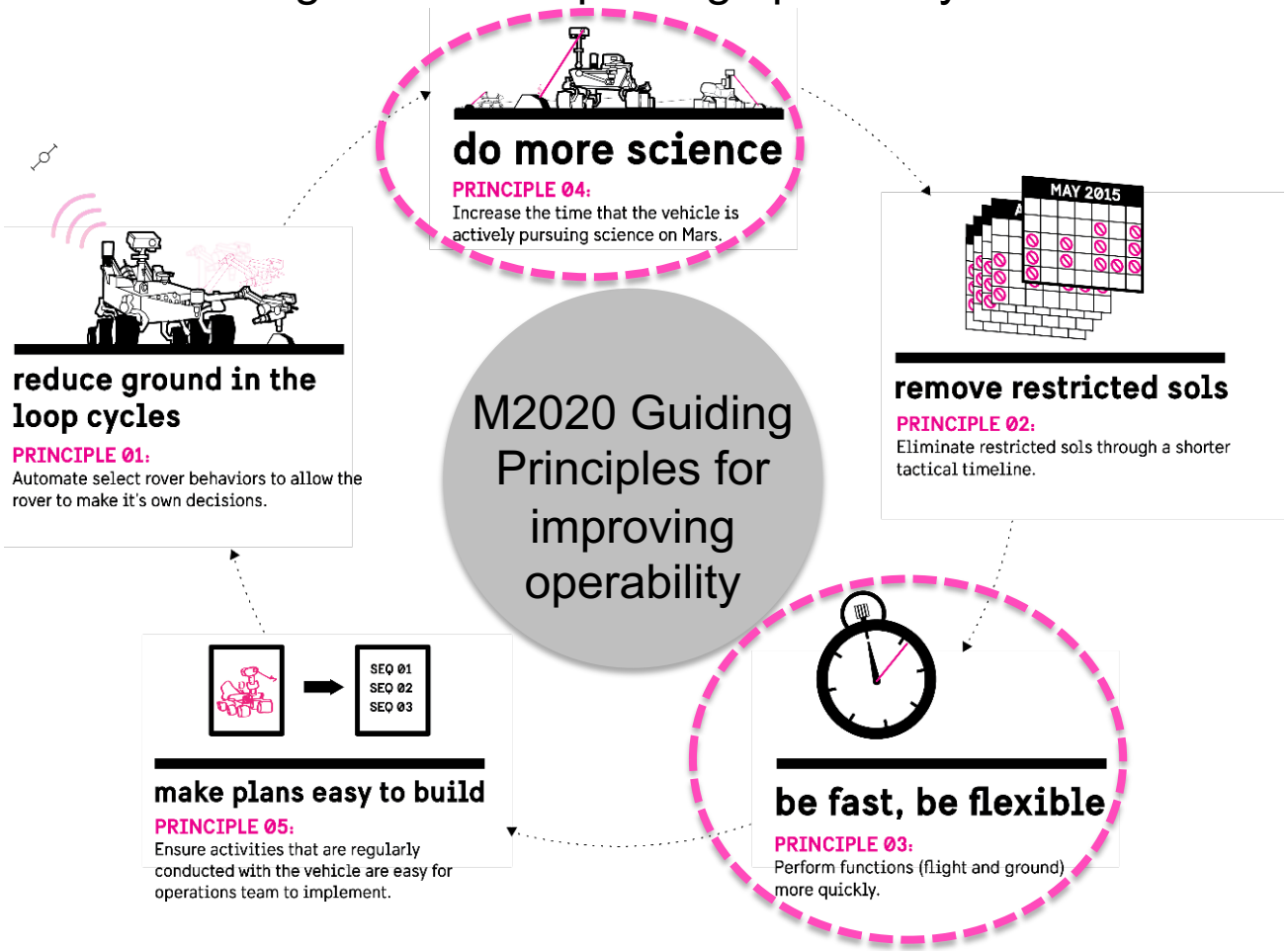

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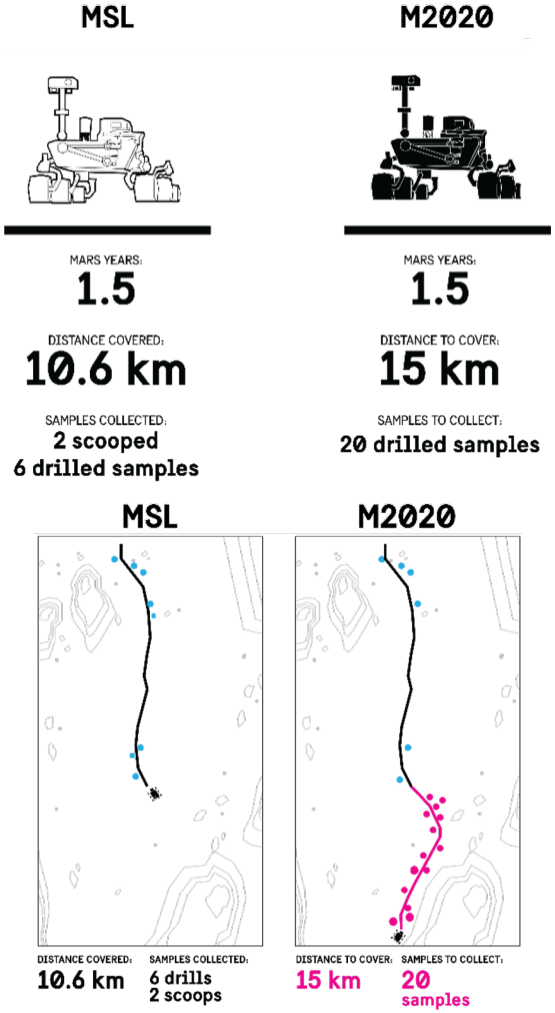


*** Images from Jennifer Trosper**

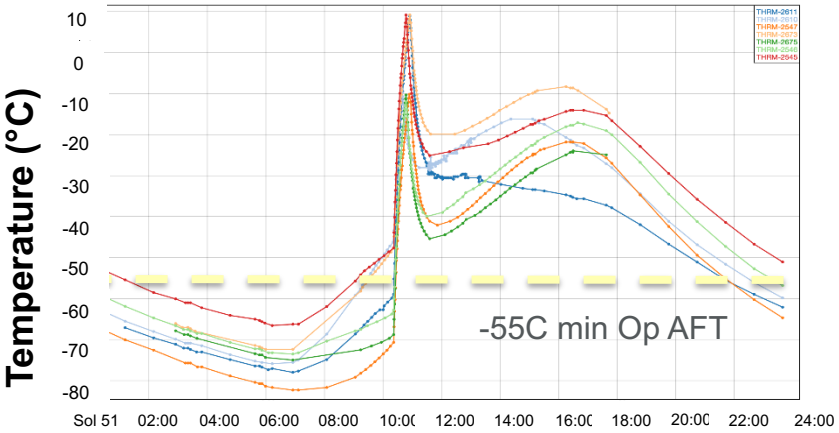
Summary of Operability Improvements

	MSL	Mars 2020
Mobility Actuator PRTs	1 PRT per mobility actuator; only half (5/10) of the mobility actuator temperature can be read at once.	2 PRTs per mobility actuator; all 10 mobility actuators can be read at the same time.
Robotic Arm (RA) PRTs	Each RA actuator had 2 PRTs on the input side only.	Each RA actuator has 4 PRTs – 2 input and 2 output side PRTs.
Actuator Thermal Modeling	Account for ball bearing conduction using vacuum, but neglect gear-to-gear conduction [1].	Instrumented thermal testing has given us the confidence to account for both ball bearing and gear-to-gear conductance accounting for CO_2 enhancement [2,3].
Warm Up Algorithms	Algorithms based on season (Ls) and time of day (LTST).	Algorithms use real time PRT data to inform warm ups and operations.
Landing Site Selection	Landing site selection was not as informed by thermal or general operability considerations.	Landing site selection has been provided significant input from the thermal and operations teams.

Main Focus of This Presentation

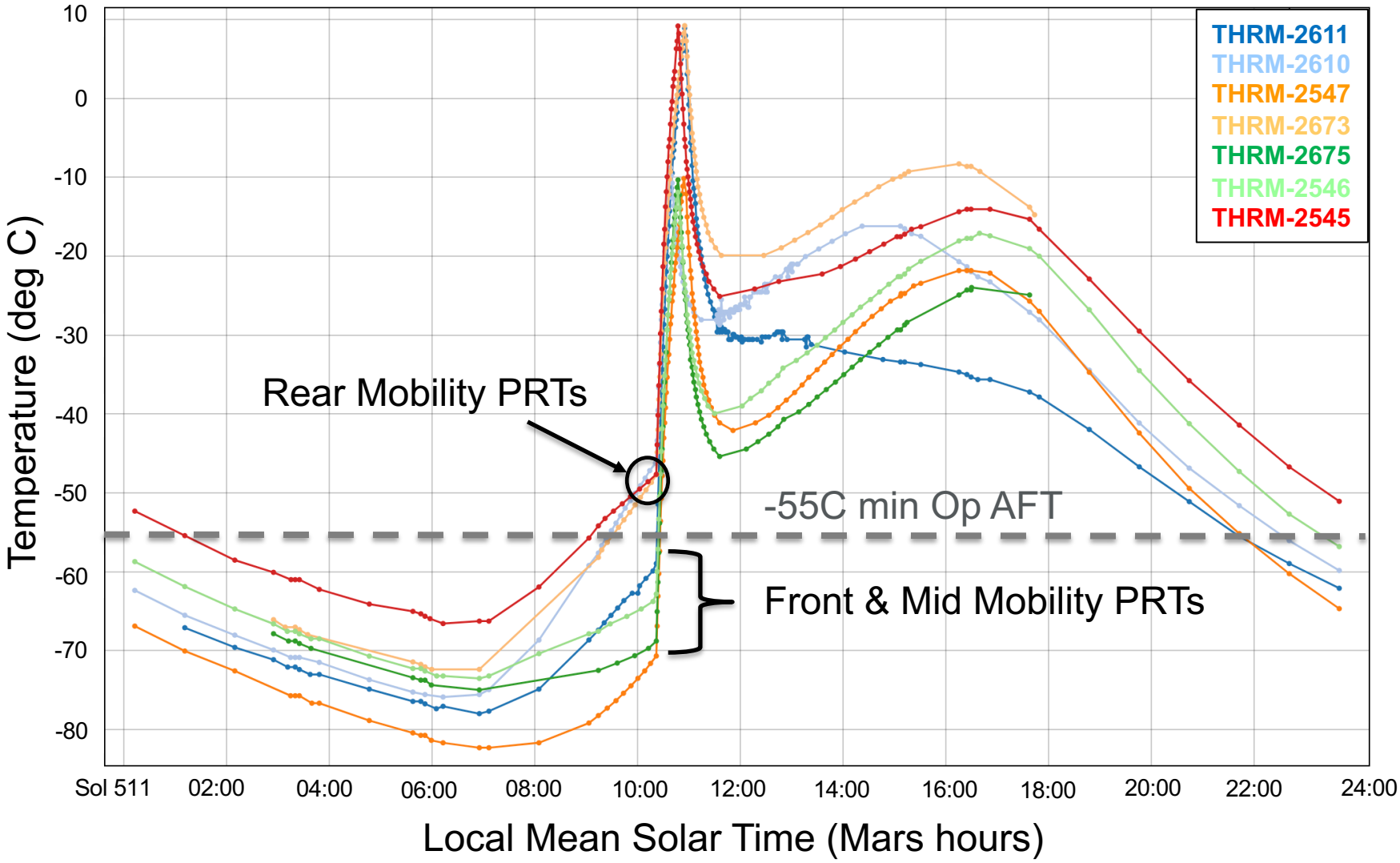
Heater Tables On MSL
(a.k.a. the biggest challenge for thermal operability)

- MSL used heater tables to prescribe warm-up times, target temperatures, and expected energy consumption.
  - These tables were a function of hardware location, season, time of day, and bus voltage.
    - Generating tables took a significant amount of time.
    - Seasonal resolution was coarse.
  - These tables were cold-biased for conservatism.
    - Heater tables often overestimate warm up time and energy by ~ 2x.
    - The effect is accentuated by RTG warming in some locations.
    - Significant variability between mechanisms in the same heater zone is common.

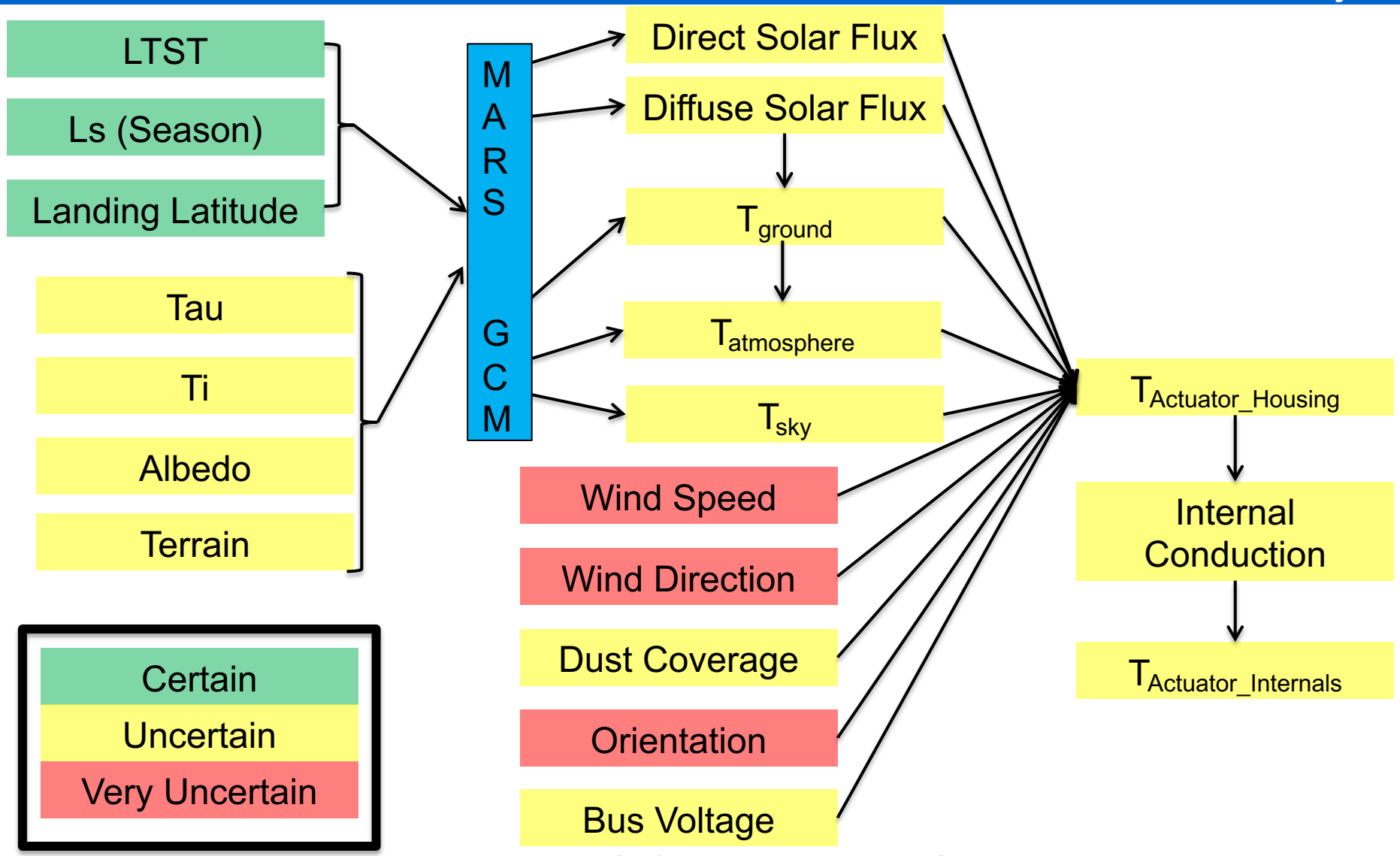


One of the biggest challenges with heater table prescription is all of the uncertainties involved!

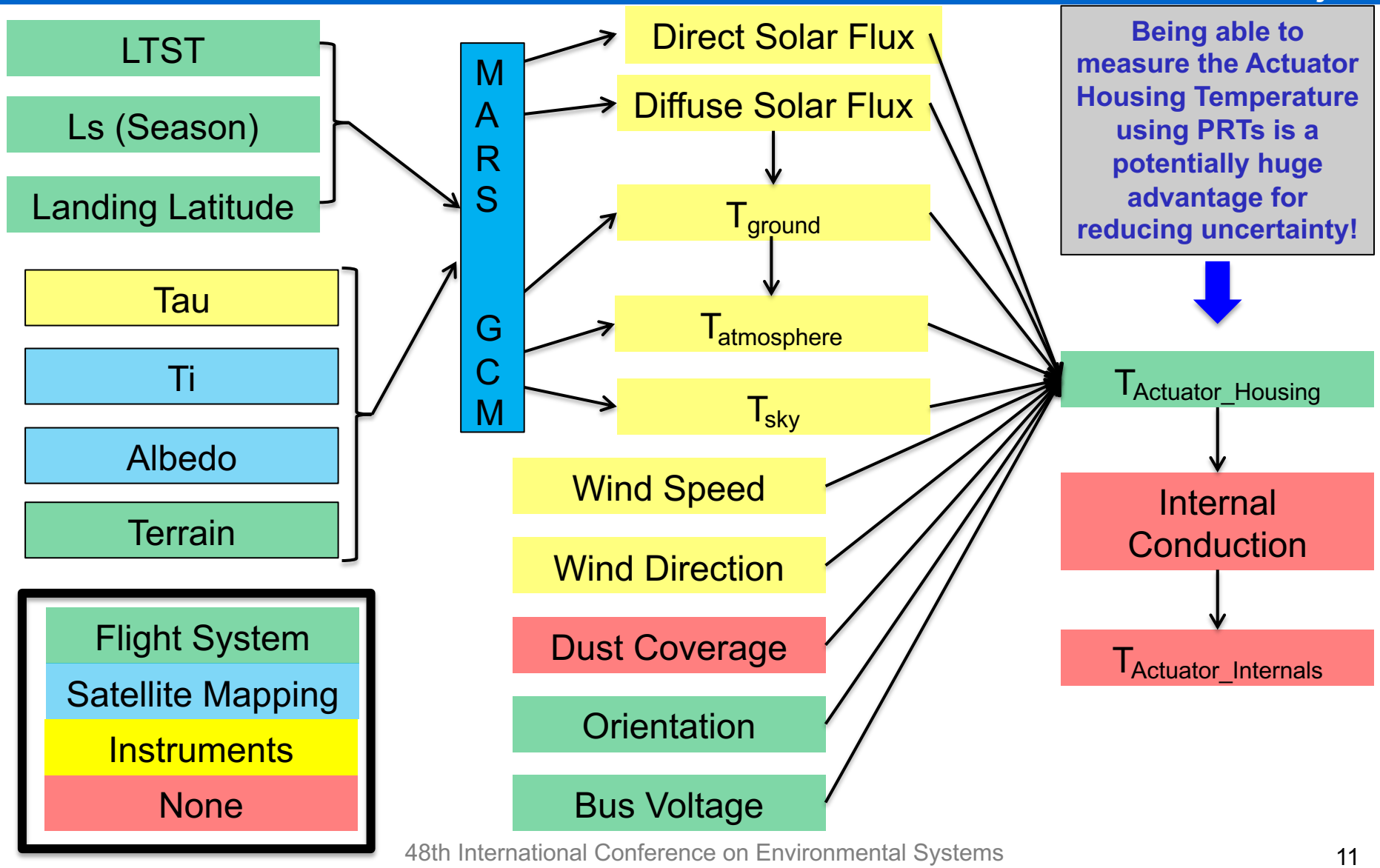
MSL Mobility Warmup on Sol 511



Uncertainty of Variables



MSL / Mars 2020 Measurement Capability



Warm-up Heating Vocabulary

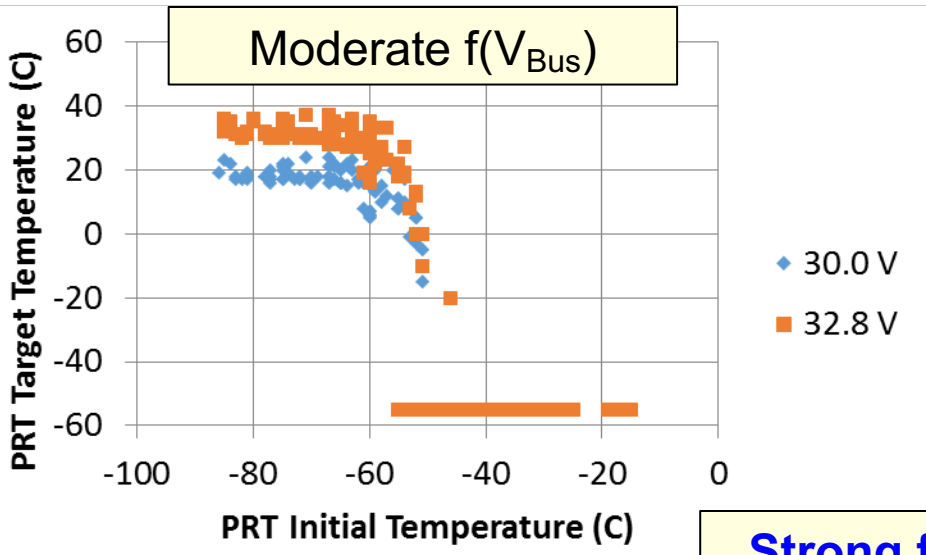
- **Keep Out Window:** Window of time when a mechanism cannot be used due to un-heated hardware that is not warm enough (ex: flex cables or cable harness)
- **No Heat Window:** Window of time when a mechanism does not need heating since it has warmed above its AFT due to environmental heating.
- **Warm Up Heating:** Active heating of a mechanism prior to use.
- **Maintenance Heating:** Active heating of a mechanism to ensure that it remains above its AFT once it has already been warmed up.
- **Target Temperature:** Warm up temperature that must be reached for a zone to be ready to use.
- **Target Time:** Minimum amount of time needed to warm up a zone to be ready to use.
- **High Setpoint**: Upper setpoint for maintenance heating
- **Low Setpoint**: Lower setpoint for maintenance heating

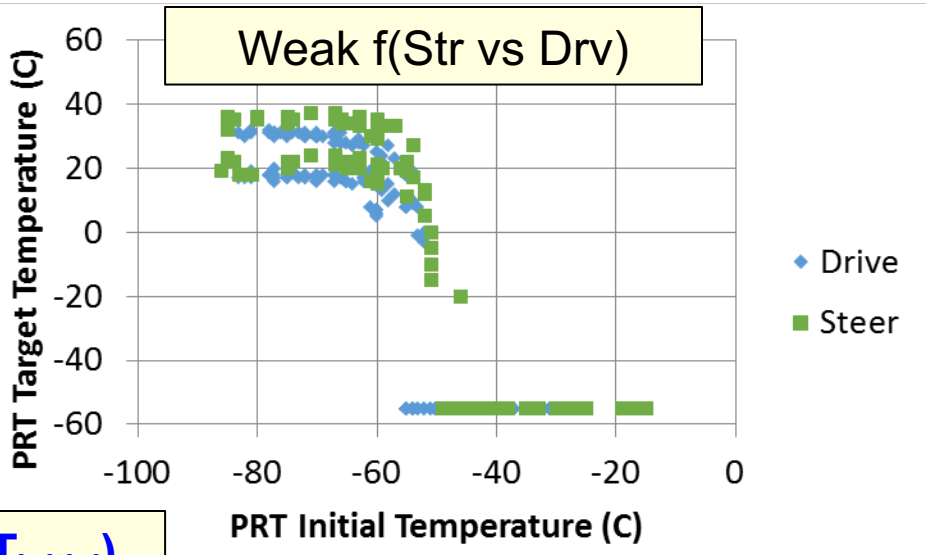
MSL vs Proposed Mars 2020 Approach

	MSL Approach – model based	Proposed Approach – model and telemetry based
"Keep Out" Windows for Unheated Hardware	Defined by Ls and LTST	**Same as MSL**
"No Heat" Windows for Heated Hardware	Defined by Ls and LTST	**Real Time Ops**: Based on PRT initial temperature **Ops Planning**: Based on anticipated PRT reading
Warm Up Heating	Defined by Ls and LTST	**Real Time Ops**: Based on PRT initial temperature **Ops Planning**: Based on anticipated PRT reading
Maintenance Heating	Defined by Ls and LTST	**Same as MSL**

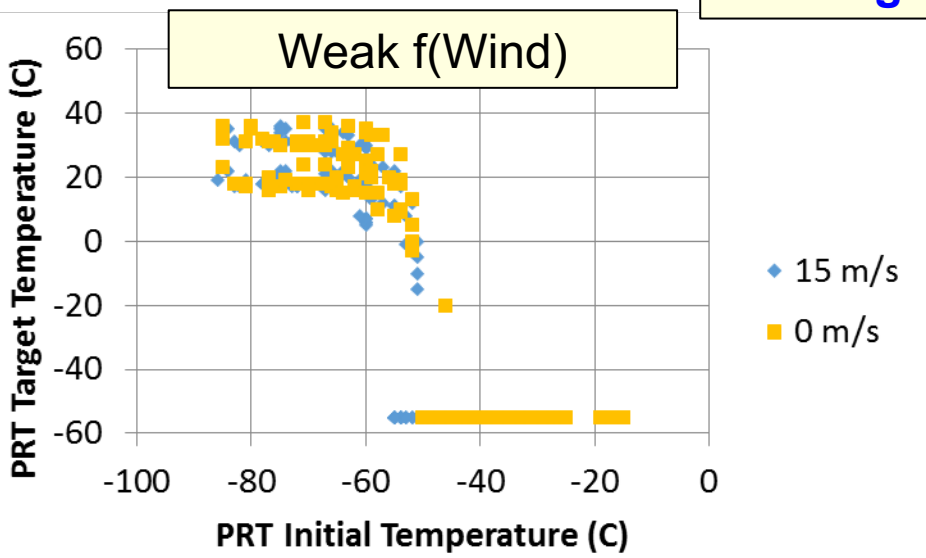
- The proposed Mars 2020 approach was evaluated using the 36 mobility model runs with various conditions:
  - 0900, 1200, and 2100 LTST warm up start time (3 variables)
  - Bin 3, 4, and 5 Environments (3 variables)
  - 30.0, and 32.8 V Bus Voltage (2 variables)
  - 0 and 15 m/s wind (2 variables)
- Since the mobility model has 10 actuators, this produced 360 data points.

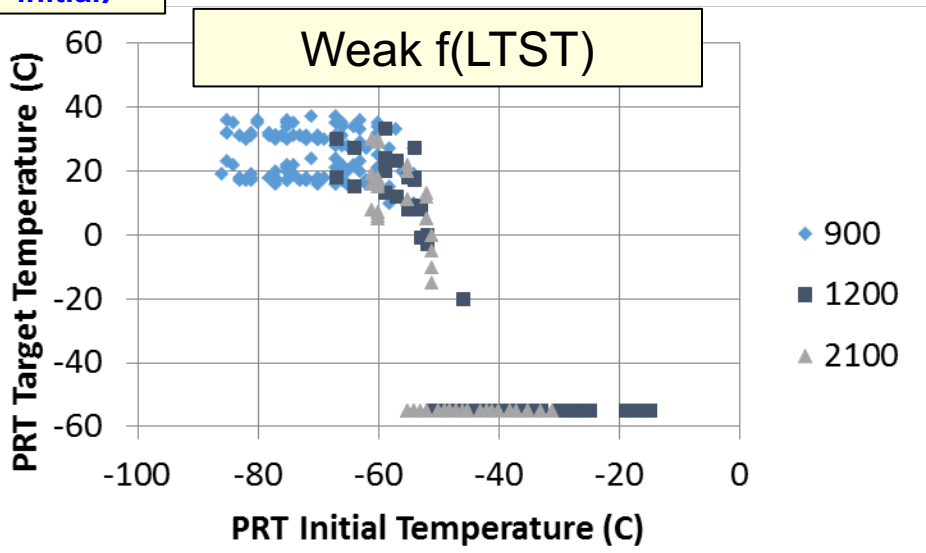
PRT Target Temperature (360 Data Points)



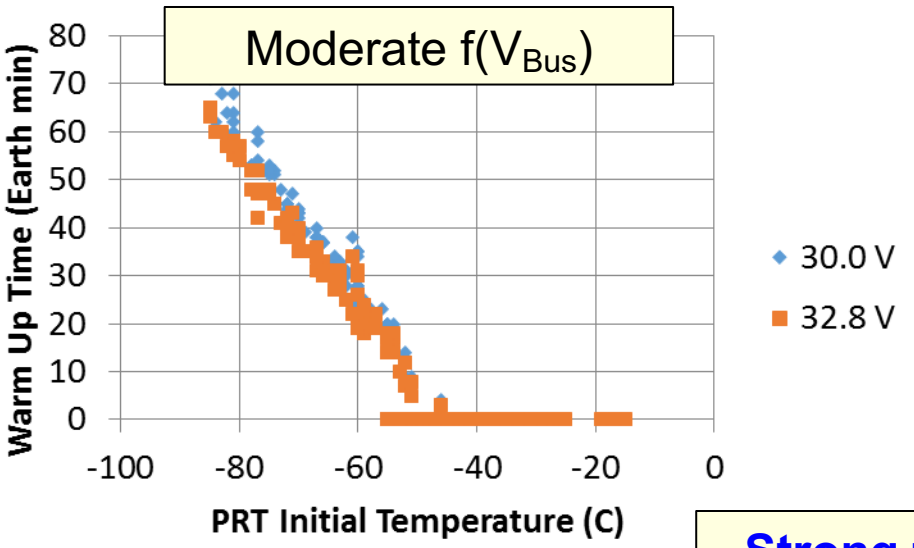


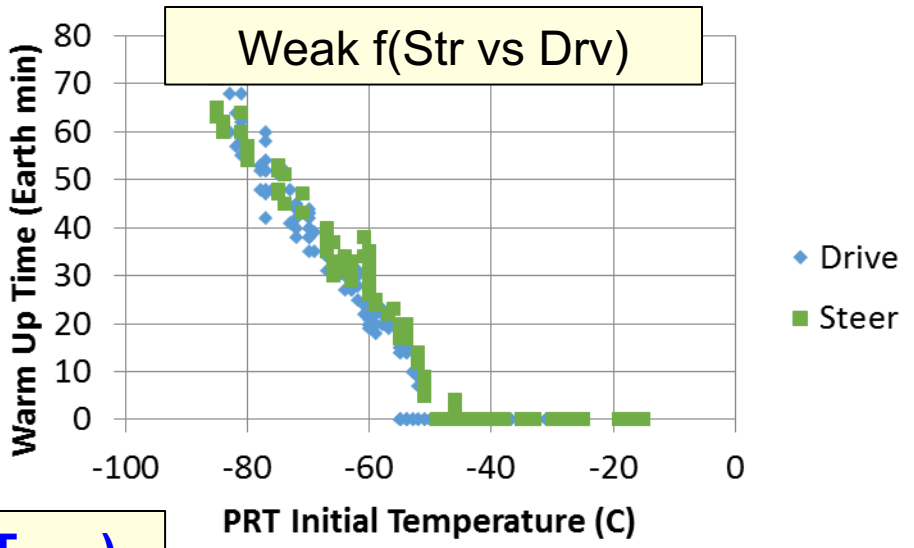
Strong f($T_{initial}$)





Warm Up Time (360 Data Points)





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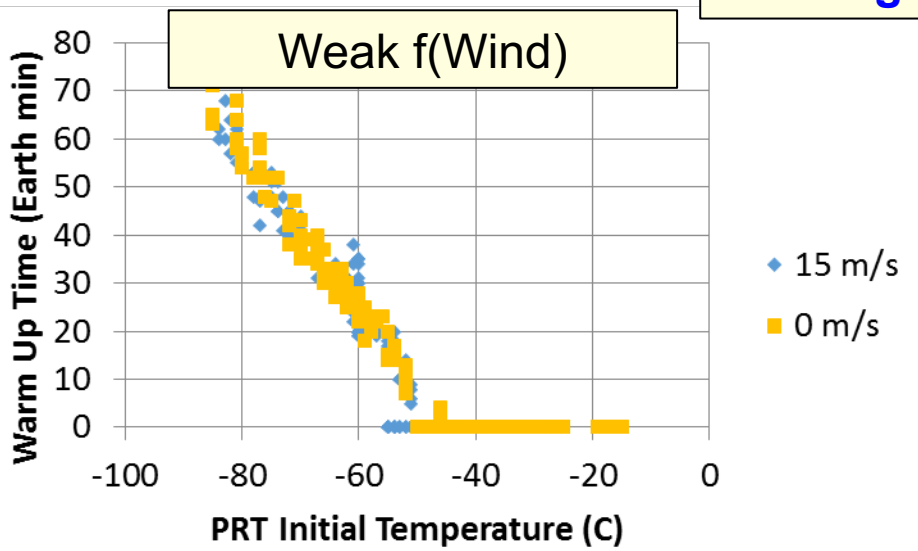
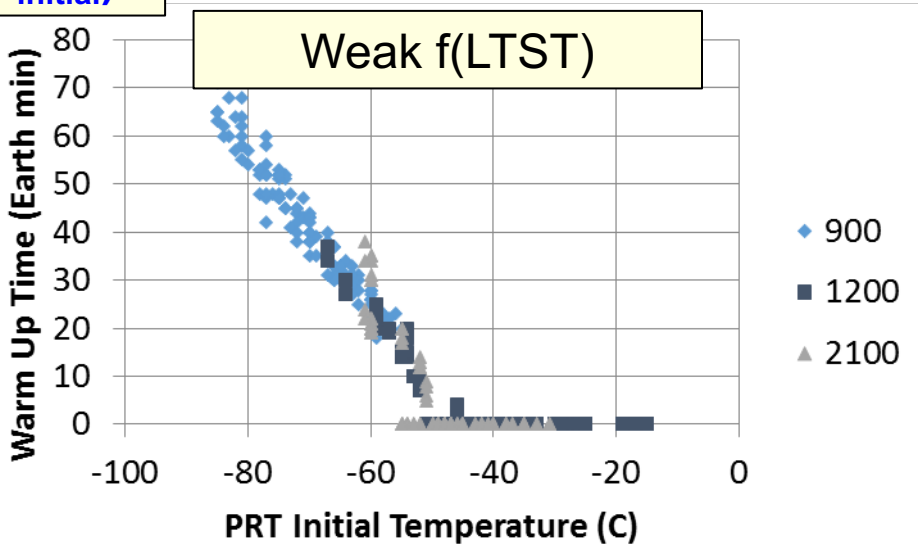
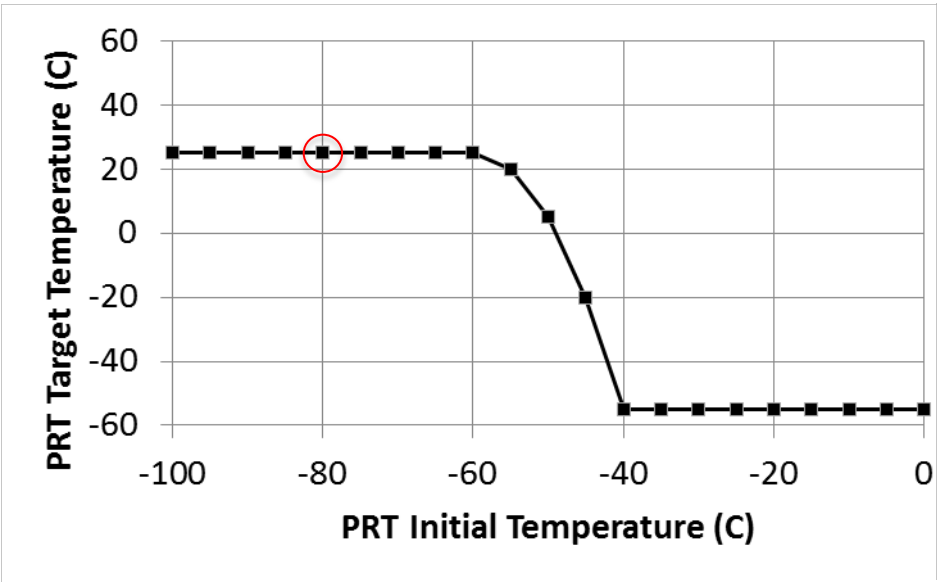
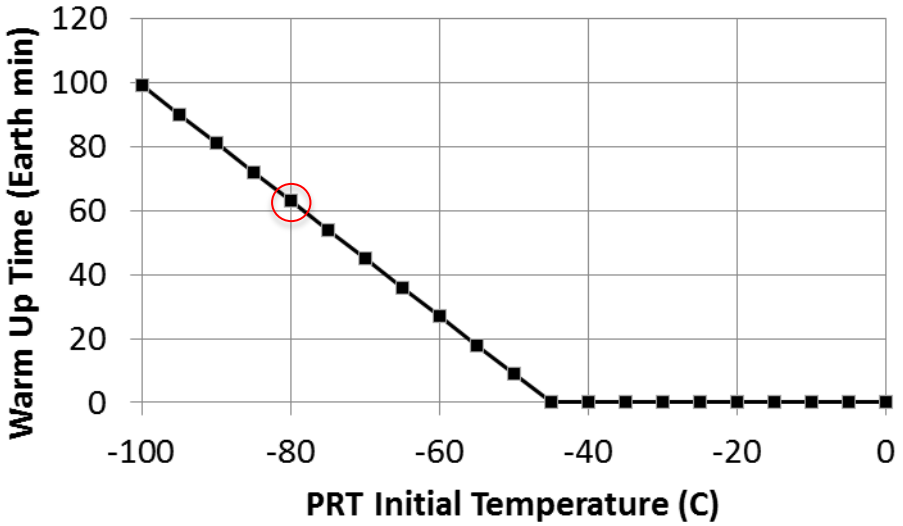




Proposed Mobility Warm Up Algorithm

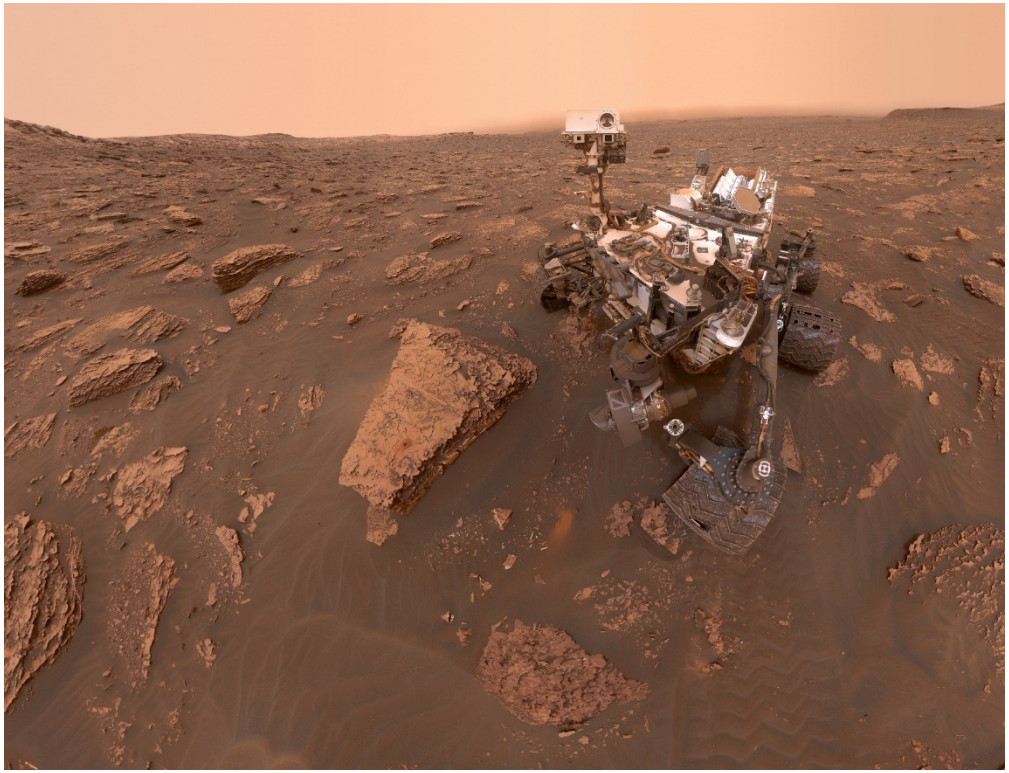
- Target Temperature and Target Time assume a nominal 31.0 V Bus Voltage.
  - For V_{Bus} > 31.0 V, then the target temperature will be reached early and the zone will have to hold that temperature until the target time is met.
    - Since higher bus voltages warm hardware faster, holding the target temperature for the whole warm up time ensures internals will be well above their AFT. This is a form of time margin.
  - For V_{Bus} < 31.0 V, then the target temperature will be reached late.
    - Since lower bus voltages warm hardware slower, by the time the target temperature is reached the internals will be well above their AFT. This is a form of temperature margin.





Conclusions

- Mars 2020 has benefited from the strong foundation created by MSL.
- Major difference between MSL & M2020 is switch from uncertain/conservative model-based heating predictions to use of real-time telemetry to drive heating prescriptions
- Mars 2020 has taken lessons learned from MSL to make the new rover more autonomous, easier to operate, and even more scientifically productive.
  - The most significant planned change from a thermal perspective is how heater tables are generated and used.
  - Operational efficiency is expected to be significantly improved by using real-time PRT temperature measurements.



Curiosity Selfie in Sol 2082 Dust Storm – Gale Crater

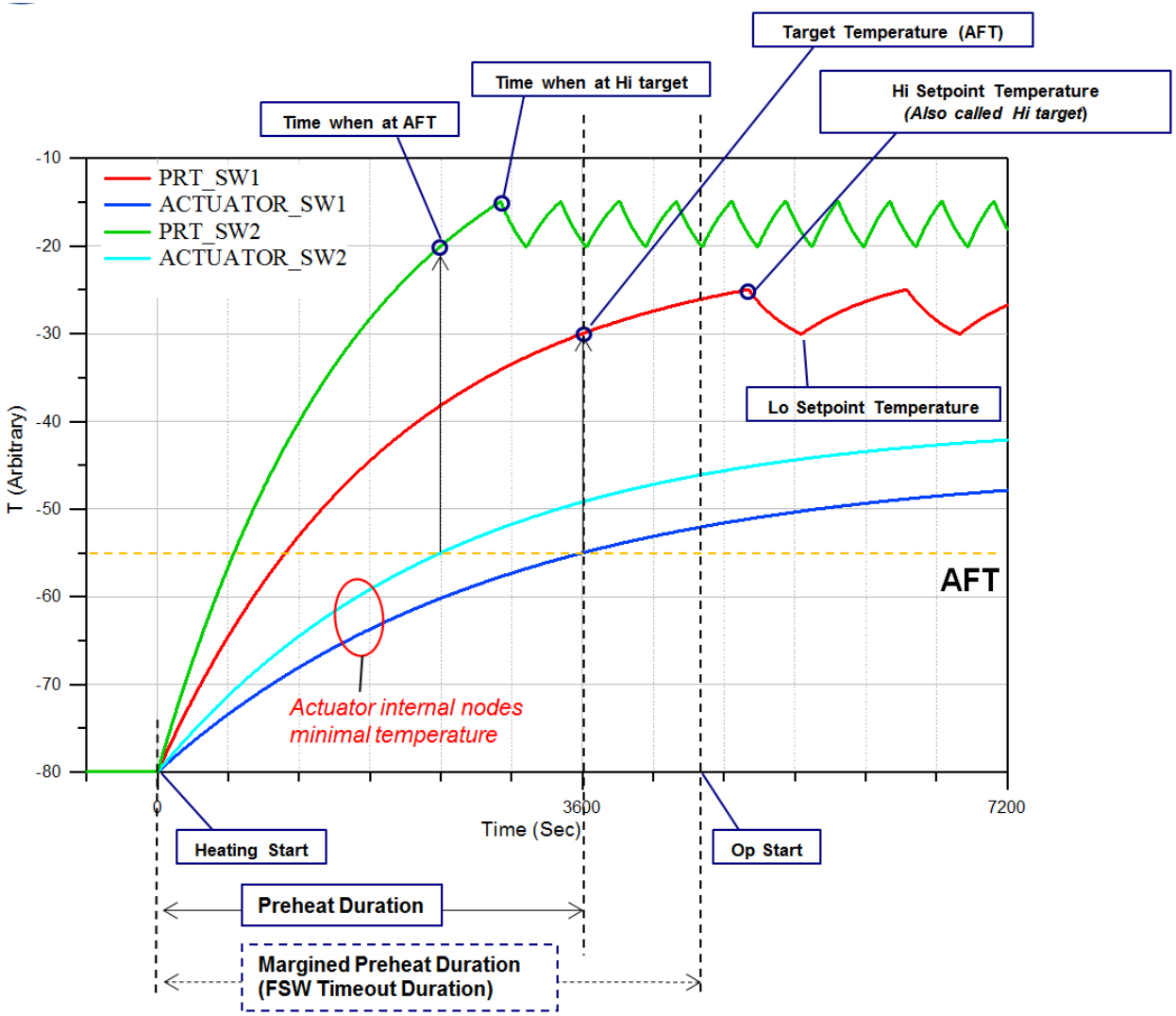
Acknowledgements

- The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

- We would like to thank Steve Kuhn, Rob Lange, Jessica Samuels, and Jennifer Trosper for their support in a number of discussions related to operability, flight software, and systems engineering for the Mars 2020 rover. Without their inputs, this work would not have been possible.

BACKUP

MSL Actuator Warm Up Tables



In Earth minutes

Preheat Duration (minutes)
Margined Preheat Duration (minutes)
Target Temperature (°C)
Lo Setpoint Temperature (°C)
Hi Setpoint Temperature (°C)
Duty Cycle (%)

RA	OP start, LTST
	OP end, LTST
	Heating start, LTST
	Warmup time (hr)
	Warmup Energy (W-hr)
	Maintenance Energy (W-hr)
	Total Energy (W-hr)
Arm_AzElv	Time when at AFT, LTST
	Time when at Hi target, LTST
	Warmup time (hr)
	Target temperature (AFT)
	Maintenance setpoint (Lo)
	Maintenance setpoint (Hi)
	Warmup Energy (W-hr)
	Maintenance Energy (W-hr)
	Duty cycle

2

MSL Actuator Heating Tables

- **Based entirely on conservative predictions**
- **Generate soak curve**
- **Then run warmup simulation run for each hour of day**

SEASON:	Winter, Ls90																
Table Name:	*Heater_Table_Ls90_2013_0128*																
Start Use Date:	2013-08-01		Start SOY:	xxx		Start Ls:	1										
End Use Date:	2014-06-22		End SOY:	xxx		End Ls:	150										
User Supplied Sol Number :	544					*Winter Solstice, Ls=90, Sol= 544 – Feb 15, 2014*											
						1st day after fall equinox											
						end of 1st martian year											
Heater System	**Quantity**																
MOB_L&R_Drive	**LTST:**	**8:22**	**8:23**	**9:00**	**10:00**	**11:00**	**12:00**	**12:55**	**13:00**	**14:00**	**14:42**	**15:00**	**16:00**	**17:00**	**17:50**	**17:51**	**17:52**
	LMST:	**8:06**	**8:07**	**8:44**	**9:44**	**10:44**	**11:44**	**12:39**	**12:44**	**13:44**	**14:26**	**14:44**	**15:44**	**16:44**	**17:34**	**17:35**	**17:36**
PRT: THRM-2545 (THRM-T-A	Preheat Duration (minutes)		124.1	115.8	94.7	76.3	62.3	46.1	44.5	23.2	0.0	0.0	0.0	0.0	0.0	0.0	
PRT: THRM-2675 (THRM-T-A	Margined Preheat Duration (minutes)		124.1	115.8	94.7	76.3	62.3	46.1	44.5	23.2	0.0	0.0	0.0	0.0	0.0	0.0	
PRT: THRM-2611 (THRM-T-A	Target Temperature (°C)		17.7	16.5	12.2	8.9	6.6	2.3	1.8	-6.5	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	
PRT: THRM-2754 (THRM-T-A	Lo Setpoint Temperature (°C)		-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-300.0	
	Hi Setpoint Temperature (°C)		-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-300.0	
	Duty Cycle (%)		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-100.0	

Legend:	
	Hardw are Too Cold (Soak)
	Operable, but not yet analyzed
	No-Heat op w indow (AFT+5C)
	No Preheat
	No Maintenance
	Maintenance setpoint optimized
	By extrapolation